Greenhouse gas emissions from shale gas and coal for electricity generation in South Africa

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There is increased interest, both in South Africa and globally, in the use of shale gas for electricity and energy supply. The exploitation of shale gas is, however, not without controversy, because of the reported environmental impacts associated with its extraction. The focus of this article is on the greenhouse gas footprint of shale gas, which some literature suggests may be higher than what would have been expected as a consequence of the contribution of fugitive emissions during extraction, processing and transport. Based on some studies, it has been suggested that life-cycle emissions may be higher than those from coal-fired power. Here we review a number of studies and analyse the data to provide a view of the likely greenhouse gas emissions from producing electricity from shale gas, and compare these emissions to those of coal-fired power in South Africa. Consideration was given to critical assumptions that determine the relative performance of the two sources of feedstock for generating electricity – that is the global warming potential of methane and the extent of fugitive emissions. The present analysis suggests that a 100-year time horizon is appropriate in analysis related to climate change, over which period the relative contribution is lower than for shorter periods. The purpose is to limit temperature increase in the long term and the choice of metric should be appropriate. The analysis indicates that, regardless of the assumptions about fugitive emissions and the period over which global warming potential is assessed, shale gas has lower greenhouse gas emissions per MWh of electricity generated than coal. Depending on various factors, electricity from shale gas would have a specific emissions intensity between 0.3 tCO_2/MWh and 0.6 tCO_2/MWh, compared with about 1 tCO_2/MWh for coal-fired electricity in South Africa.

Introduction

South Africa is heavily dependent on coal for its primary energy supply, and is looking towards alternatives for electricity supply both in the interests of reducing the greenhouse gas (GHG) emissions intensity of its electricity supply and of seeking to diversify its energy sources. Shale gas potentially represents an alternative to coal for both electricity and energy supply. Reserves of shale gas in South Africa have been estimated to be the fifth largest globally, with current estimates placing reserves at 500 trillion cubic feet (tcf), although this figure can only be proved by exploration.[1,2]

When considering fuel combustion and electricity generation only, the GHG emissions associated with the production of electricity using gas (be it natural or shale gas) are definitely lower than those associated with electricity produced from coal. There have, however, been some studies that suggest that this may not be the case when considering the full life-cycle impacts, including those associated with fuel production and transport. In particular, fugitive emissions of methane increase the GHG impacts of this fuel option; fugitive emissions are those associated with leaks at various stages of fuel production such as during exploration, drilling and gas transport.

In this review, we summarise a selection of global studies to demonstrate some of the diverging findings on the GHG implications of shale gas, and highlight the critical assumptions that determine the results of such studies. The GHG emissions associated with the extraction of shale gas are then compared with those during electricity production from coal in South Africa.

The high contribution of fugitive emissions to the overall footprint of shale gas is in part because methane has a higher global warming potential (GWP) than carbon dioxide. In addition to exploring the magnitude of fugitive emissions, some studies have assessed the impact of assumptions around the time horizons of methane on the results, with assumptions of a shorter time horizon resulting in an even higher impact of fugitive emissions on the overall GHG footprint than when the GWP over a 100-year horizon is used. Some consideration is also given in this paper to the impacts of assumptions on GWP on the results.

It is recognised that both mining of coal and shale gas extraction have environmental and social impacts beyond those relating to their contribution to global warming, notably those on water resources. A discussion of such impacts is beyond the scope of this article.

Assumptions about global warming potentials and timescales

Prior to presenting the results from various studies on the GHG implications of shale gas versus coal, it is important to understand the science underlying one of the critical assumptions which has a substantial impact on the results: the GWP of methane, along with the timelines for which its impact is assessed.

Because multiple gases, including both carbon dioxide and methane, contribute to climate change, an emissions metric is needed to put emissions of different GHGs on a common basis when designing policies and measures to reduce GHG emissions. GWPs are one of the most commonly used 'conversion factors' for this purpose. The GWP is a multiplier that is used to convert a quantity of emissions of a gas species to an equivalent quantity of carbon

dioxide (often referred to as CO_2-equivalent or CO_2e). Carbon dioxide is the major GHG in terms of overall contribution – despite its lower GWP relative to methane, the volumes emitted are much larger. This fact is most clearly seen in the contribution to radiative forcing, which for CO_2 is 1.66 W/m^2 (range 1.49–1.83 W/m^2) compared with a CH_4 radiative forcing of 0.48 W/m^2 (range 0.43–0.53 W/m^2).[3]

There are other very general formulations of an emissions metric (see for example Kandlikar[4]), but they suffer from difficulties, notably definition of the impact function and treatment of the time horizon. Other metrics, such as the Global Temperature Potential (GTP) have also been considered. GTP gives 'equivalent climate responses at a chosen time' and there is less focus on the fluctuations in the shorter term than when choosing a 20-year time horizon for methane.[5]

Hence the 'simpler and purely physical GWP index' was developed which compared the radiative forcing of a unit pulse, e.g. 1 kg, integrated over a time horizon (discussed further below). GWPs were also used in the Kyoto Protocol and its flexible mechanisms.[3] After comparing various options, the Intergovernmental Panel on Climate Change (IPCC) indicated that 'GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases'[5]. The GWP is thus used here, and a discussion of other metrics is beyond the scope of this paper.

It is recognised, however, that several simplifications are made in developing the GWP multipliers. These simplifications, which are required in order to produce a workable emissions metric, have attracted criticisms of GWP. Among these are the impact function, but also (and most relevant to natural or shale gas) the assumptions about time horizons. The time horizon is particularly important in relation to gas, including shale gas. The residence time of CO_2, the most abundant GHG, in the atmosphere is between 50 and 200 years,[6] whereas methane remains for a much shorter period of 10 years.[7]

The IPCC's assessment reports have included GWPs for several gases and for different time horizons, with various factors leading to revision of these factors. The last comprehensive assessment of GWPs was undertaken by Working Group I of the IPCC in its Fourth Assessment Report (AR4). Working Group I focused on the physical science basis of climate change. The IPCC's AR4 reported the 100-year GWP of methane as 25 (the Second Assessment Report in 1995 suggested a lower value at 21) and the 20-year GWP of methane as 72 (56 in the Second Assessment Report).[6,8,9] The Fifth Assessment Report[10], due to be released in 2014, reviews these factors again. The studies cited here used GWPs from the Fourth Assessment Report. The Fifth Assessment Report provides updated GWPs (and other metrics), including GWPs over 20- and 100-year time horizons, with and without climate-carbon feedbacks (cc fb). For methane, AR5 reports GWP_{100} without cc fb as 28, with cc fb as 34, and GWP_{20} without cc fb as 84 and with cc fb as 86. Changing these values in our analysis would reduce their utility, as they would not be comparable to the literature; the general patterns reported hold.

The contribution of CO_2 and CH_4 to radiative forcing is well understood, with CO_2 making the greater contribution. The IPCC assessment[3] made it clear that the time horizon for assessment cannot be determined on a scientific basis alone, but that value judgements are required. In applying GWPs in a policy context, the crucial additional consideration in selecting a time horizon for the GWP metric is about the goal and purpose. Since that assessment report,[3] there has been political convergence on a long-term temperature stabilisation goal, within fairly narrow bounds of 2 °C, strengthening to 1.5 °C. Given that the goal of limiting temperature increase is now quantified, analysis can be aligned to the purpose of preventing the *long-term* increase in maximum temperature, which requires consideration of a longer time horizon and stabilisation of GHG concentrations (the objective of the United Nations Framework Convention on Climate Change[8]). Our view is that it seems advisable to retain the current practice of focusing on the GWP of non-CO_2 GHGs over a 100-year time horizon.

Life-cycle emissions from fuel supply

Sources of emissions from coal production

Coal production includes mining, preparation or beneficiation (depending on the coal quality and use) and coal transport. Coal mining is either conducted in underground or open-cast mines. GHG emissions sources from coal supply include:

- GHG emissions from electricity generation and diesel usage in mining. These emissions are primarily carbon dioxide although small volumes of other GHGs are also produced.
- Emissions associated with coal transport (electricity for conveyors, diesel for trucks and electricity and diesel for trains).
- Methane from coal seams that is released during exploration, venting of seams and ventilation of shafts.
- Spontaneous combustion of discards and disused workings, resulting in further CO_2 emissions.

While quantification of the first two sources is relatively straightforward, quantification of the methane emissions from coal seams and CO_2 emissions from spontaneous combustion is more difficult.

For underground coal mining, the majority of GHG emissions are in the form of methane that was previously retained in the coal seam. This methane is currently vented in South African mines. The remainder of the emissions from underground mines are GHG emissions associated with electricity use by the mine, and to a lesser extent combustion of liquid fuels. However, in open-cast mines, methane emissions released from the coal seam account for only a small portion of the total GHG emissions (less than 2%), with emissions associated with electricity use or liquid fuel use accounting for the majority of GHG emissions (depending on the mining method employed). De Wit[11] suggests that GHG emissions from coal mining and fugitive emissions are, however, small relative to those from combustion (6.55 Mt of CO_2-e emissions in 2003) and hence they are excluded from this current analysis.

Sources of emissions from shale gas supply

As indicated previously, emissions of methane can arise at various stages of the gas supply chain:

- well completion
- routine venting, equipment leaks and gas processing
- liquid unloading
- transport, storage and distribution

These sources of emissions are described in more detail below.

The World Resources Institute has produced a guideline for defining the boundary of which life-cycle impacts from shale gas production should be considered in determining the fuel impacts.[12] The World Resources Institute report reviews a number of studies to determine how extensively life-cycle impacts are incorporated into analyses. This review suggests that only one of 16 studies reviewed considered exploration, half considered site preparation and well completion, 11 considered fracking and 12 considered drilling. The substantial differences in system boundaries thus need to be taken into consideration when comparing different results, as illustrated further in this paper.

Emissions from well completion

During hydraulic fracturing ('fracking') to produce shale gas, fluid (mainly water) under high pressure is used to fracture deep shale formations. These fractures then begin releasing methane that was previously retained in the rock. The fracturing fluid is brought back to the surface over a period of between 5 and 12 days, after which methane flows freely from the well. Initially the amount of methane released during flowback is low, although it does increase significantly towards the end of the flowback period.

Different studies have produced diverging results on the amount of methane emitted during the flowback period. Howarth et al.[13] suggest that the gas emitted during this flowback period can be estimated from the well's initial production rate, and Jiang et al.[14] support this view, assuming that the rate of methane release during flowback is the same as that for the first 30 days of production. Cathles et al.[15], however, argue that the amount of methane produced during flowback is lower and cannot be estimated from initial production rates.

The majority of methane emitted during flowback is vented or flared – the latter clearly being preferred from a GHG emissions perspective as flaring converts methane to carbon dioxide, which has a significantly lower global warming potential. There are different assumptions on the proportion of methane emissions produced during flowback which are typically vented and flared. In their analysis, Howarth et al.[13] assumed that 85% of gas produced during flow back was vented and not flared, a conservative estimate in their opinion. Howarth et al.[13] support this high venting rate. Findings of other studies suggest that this venting rate is high. Both Jiang et al.[14] and Cathles et al.[15] report that 51–100% of the gas would typically be flared, and the remainder (0–49%) vented.

Emissions during extraction and processing

An extraction site has between 55 and 150 piping connections, all of which have the potential to develop gas leakages. Other equipment such as storage tanks and dehydration equipment have also been known to leak methane. In addition to unplanned leakages, certain pieces of equipment release gas to maintain internal pressure, and some pieces of equipment, such as pneumatic valves, release gas to power themselves when electricity is not available. Where gas requires further processing to increase purity, associated equipment also potentially releases emissions from leaks and during venting.

Emissions from liquid unloading

Liquid unloading is required when water and mud collect in the well and thus reduce the flow of gas. This process usually would occur later on in a well's life and would not be required for all wells. Collection of water and mud is a common problem in conventional natural gas wells but less of a problem in shale gas wells. During the unloading process, operators shut the well off to increase the pressure within the well. When the well is opened again, the pressure of the gas pushes liquid up and out of the well.[16] Gas is released during this process.

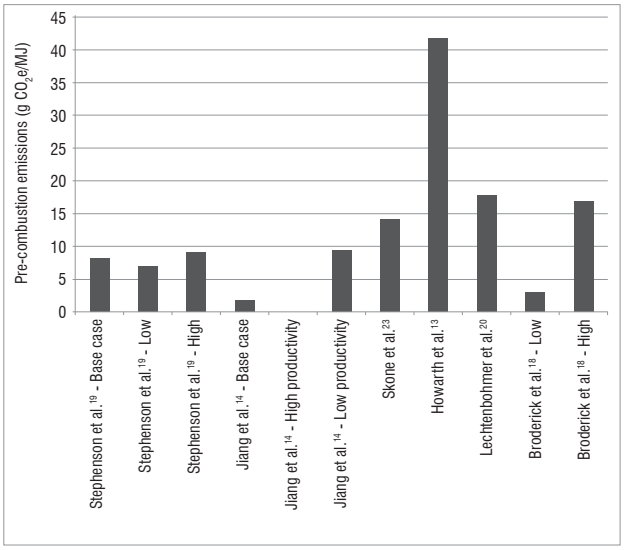
Emissions during transport, storage and distribution

Transmission, storage and distribution emissions are similar to those mentioned in the section on upstream extraction and processing, that is, those related to leaks and venting.

Quantifying the emissions from shale gas supply

A range of studies have been conducted which have focused on assessing the life-cycle emissions of shale gas, with the aim of determining the benefits of shale gas over conventional gas, coal and oil. Figure 1 shows a comparison among estimates of the emissions from shale gas supply up to the point of combustion, from a variety of different studies.[17]

From Figure 1 it can be seen that the majority of estimates of pre-combustion emissions are within a similar range, with the exception of the 'high' estimates of Broderick et al.[18], the estimates of Lechtenböhmer et al.[20] and those of Howarth et al.[13]. The Howarth et al. study received substantial attention as a result of its indications that emissions from shale gas were higher than those of other fossil fuels; however, a number of aspects of their analysis (including input assumptions and calculation errors) have come under criticism in subsequent studies, yielding significantly different results and questioning their higher overall GHG implications.[15,17] Howarth et al.[13] also chose to use a GWP for methane of 33, rather than that of 25 as used by other studies; however, this has been corrected for in Figure 1 to bring all of the studies on to the same basis with respect to GWP.



Note: *Jiang et al.[14] 'high productivity' and 'low productivity' refer to wells with high and low flow rates and lifetimes, respectively. The 'low', 'high' and 'base cases' in Stephenson et al.[19] refer to the extent of recovery which were explored by varying the impact of a number of different variables including ultimate recovery from the well, well completion emissions, flowback water, fractures per well and wellhead pressure.*

Figure 1: Pre-combustion emission estimates from shale gas (g CO_2e/MJ) obtained from different studies.

In interpreting the results presented in Figure 1, it needs to be recognised that the different studies do not all incorporate all of the steps in the pre-combustion supply of shale gas. Table 1 presents a breakdown of the steps included and excluded from the various studies. It also shows the substantially higher assumptions about well completion emissions included in the Howarth et al.[13] and Broderick et al.[18] studies. Note that the figures shown in Table 1 were calculated using a 100-year GWP for methane of 25, as per IPCC AR4.

Table 1: Breakdown of pre-production and pre-combustion emissions (g CO_2e/MJ) from shale gas

	Stephenson et al.[19]			Jiang et al.[14]			Skone et al.[23]	Howarth et al.[13]	Lechtenböhmer et al.[20]	Broderick et al.[18]	
	Base case	Low	High	Base case	High productivity	Low productivity				Low	High
Well completion	1.8	0.9	2.9	1.8	0.1	9.2	7.8	23.4	9	3	16.9
Venting, equipment leaks and gas processing	4.2	4.2	4.2				3.5	2.2	8.9		
Liquid unloading											
Transport, storage and distribution	1.9	1.9	1.9				2.7	16.2			
Pre-combustion total	7.9	7	9	1.8	0.1	9.2	14	41.8	17.9	3	16.9

Source: adapted from Forster and Perks[17]

Comparing electricity from shale gas and coal in South Africa

We have presented the outcomes of various other studies on the GHG emissions from shale gas. What is of particular interest in South Africa is comparing the range of potential emissions from using shale gas for electricity generation with emissions from coal-fired power generation, as coal is currently the predominant fuel for electricity generation, and there are emerging interests in shale gas in the country.

In 2012, Eskom produced 218 212 GWh from their coal-fired power stations (including own use), with associated emissions of 231.9 Mt CO_2, suggesting an emissions intensity of 1.06 tCO_2/MWh for coal-fired power alone.[21] The overall emissions intensity associated with electricity in South Africa is somewhat lower, because of the presence of other lower emissions options in the generation mix. It is the coal-fired portion only that is of interest in this current paper. As stated above, emissions associated with coal supply were considered negligible in this study.

Gas turbines, particularly combined cycle gas turbines, that are used to burn shale gas have higher efficiencies than coal-fired power stations. Combined cycle gas turbines in the USA have an average efficiency of 46%. Newer combined cycle gas fired power stations could achieve 55% or even 65% efficiency.[13,17,22] In the analysis here, the total life-cycle GHG emissions from producing a MWh of electricity are calculated by adding the pre-combustion emissions suggested by the various studies (as shown in Figure 1) to the emissions from burning the gas in a turbine. Consideration is given to the use of an older (46% efficiency), newer (55% efficiency) and potential future high efficiency (65% efficiency) power station.

Table 2 shows the life-cycle emissions intensity of electricity generated from shale gas calculated using this approach. Once again, it needs to be recognised that not all of the studies include venting, equipment leaks and gas processing, liquid unloading and transport, storage and distribution, and hence are not directly comparable but rather provide a range of results.

Table 2 shows clearly that under a wide range of assumptions about the efficiency of conversion of gas to electricity, and under all assumptions about the pre-production emissions of shale gas, shale gas has substantially lower GHG emissions than the 1.06 tCO_2/MWh associated with electricity produced from coal in South Africa. The lowest value in Table 2 is 0.31 tCO_2/MWh and the highest is 0.59 tCO_2/MWh. The differences relate to assumptions across studies of productivity, and the assumed efficiency of combined cycle gas turbines. In other words, how much lower the carbon footprint of shale gas is depends on assumptions about efficiency, fugitive emissions and GWPs. What is further interesting to note is the percentage of the emissions shown in Table 2 that are made up by pre-combustion emissions, and those that arise during electricity generation, using the assumptions about pre-combustion emissions in the various studies. These range from 1% in the Jiang et al.[14] base case, to 8% in the Skone et al.[23] case, to 34% in the case of Howarth et al.[13]

Finally, given the debates surrounding GWP for methane, and particularly the time horizon to be used, the calculations presented in Table 2 are repeated using a 20-year GWP for methane of 72.5 These results are shown in Table 3.

Clearly, the biggest impact of the shorter GWP is on the results of Howarth et al.[13], who assume the highest methane emissions associated with pre-combustion processing. However, it is interesting to see that even using a 20-year GWP for methane, shale gas has lower GHG emissions than coal-fired power in South Africa.

Conclusions

We have highlighted some of the life-cycle GHG considerations when comparing electricity generation from coal with that from shale gas in South Africa, and provided a comparison of emissions between the two electricity generation options. While a wide range of data is presented in the literature on the fugitive emissions from shale gas production, with not all data sources providing comparable information, the overriding indication is that shale gas has lower GHG emissions than coal-fired

Table 2: Calculated CO_2e/MWh electricity produced under different assumptions of combined cycle gas turbine efficiency using a 100-year global warming potential for methane (own analysis)

	Stephenson et al.[19]			Jiang et al.[14]			Skone et al.[23]	Howarth et al.[13]	Lechtenböhmer et al.[20]	Broderick et al.[18]
Assumed efficiency of conversion of gas to electricity	**Base case**	**Low**	**High**	**Base case**	**High productivity**	**Low productivity**				**Low**
46%	0.47	0.47	0.48	0.45	0.44	0.46	0.48	0.59	0.51	0.45
55%	0.40	0.40	0.40	0.38	0.37	0.39	0.40	0.52	0.43	0.38
65%	0.34	0.34	0.35	0.32	0.31	0.33	0.35	0.46	0.38	0.32

Table 3: Calculated CO_2e/MWh electricity produced under different assumptions of combined cycle gas turbine efficiency using a 20-year global warming potential for methane (own analysis)

	Stephenson et al.[19]			Jiang et al.[14]			Skone et al.[23]	Howarth et al.[13]	Lechtenböhmer et al.[20]	Broderick et al.[18]
Assumed efficiency of conversion of gas to electricity	**Base case**	**Low**	**High**	**Base case**	**High productivity**	**Low productivity**				**Low**
46%	0.53	0.52	0.54	0.46	0.44	0.50	0.54	0.88	0.63	0.47
55%	0.45	0.44	0.46	0.39	0.37	0.43	0.47	0.80	0.56	0.40
65%	0.40	0.39	0.41	0.33	0.31	0.37	0.41	0.75	0.50	0.34

power. This is the case even when considering a 20-year GWP time horizon for methane, which is not typical of the literature nor considered appropriate for the purpose of limiting long-term temperature increase. Depending on various parameters examined in this article, electricity from shale gas would have a specific emissions intensity between 0.31 tCO_2/MWh and 0.59 tCO_2/MWh, compared with about 1.06 tCO_2/MWh for coal-fired electricity in South Africa.

Authors' contributions

Both authors conceptualised the paper. B.C. was the principle author and was responsible for the quantitative assessments. H.W. authored the section 'Assumptions about global warming potentials and timescales' and provided editorial input on the remainder of the text.

References

1. Botha M, Yelland C. On fracking in the Karoo, open forums and the power of public opinion. Pretoria: EE Publishers; 2011.
2. De Wit M. The great shale debate in the Karoo. S Afr J Sci. 2011;107(7), Art. #791, 9 pages. http://dx.doi.org/10.1016/S0140-9883(96)00021-7
3. Intergovernmental Panel on Climate Change (IPCC). Climate change 2007: The physical science basis. Technical summary. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Geneva: IPCC; 2007. Available from: http://www.ipcc.ch/SPM2feb07.pdf.
4. Kandlikar M. Indices for comparing greenhouse gas emissions: Integrating science and economics. Energ Econ. 1996;18:265–282. http://dx.doi.org/10.1016/S0140-9883(96)00021-7
5. Intergovernmental Panel on Climate Change (IPCC). Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Geneva: IPCC; 2007. Available from: http://www.ipcc.ch.
6. Intergovernmental Panel on Climate Change (IPCC). IPCC second assessment report. Geneva: IPCC; 1995. Available from: http://www.ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-assessment-en.pdf.
7. Boucher O, Friedlingstein P, Collins B, Shine KP. The indirect global warming potential and global temperature change potential due to methane oxidation. Environ Res Lett. 2009;4:1–5. http://dx.doi.org/10.1088/1748-9326/4/4/044007
8. United Nations Framework Convention on Climate Change (UNFCCC). New York: United Nations; 1992. Available from: http://unfccc.int/resource/docs/convkp/conveng.pdf.
9. Intergovernmental Panel on Climate Change (IPCC). IPCC fourth assessment report (AR4). Working Group 1: The physical science basis. Geneva: IPCC; 2007. Available from: http://www.ipcc.ch/publications-_and_data/ar4/wg1/en/contents.html.
10. Intergovernmental Panel on Climate Change (IPCC). Climate change 2013: The physical science basis. Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Geneva: IPCC; 2013. Available from: https://www.ipcc.ch/report/ar5/wg1/
11. De Wit M. Coal mining and carbon constraints. Final report on Task 6.1. Johannesburg: Coaltech; 2005. Available from: http://www.coaltech.co.za/.
12. Branosky E, Stevens A, Forbes S. Defining the shale gas life cycle: A framework for identifying and mitigating environmental impacts. Working paper October 2012. Washington DC: World Resources Institute; 2012.
13. Howarth RW, Santoro R, Ingraffea A. Methane and greenhouse-gas footprint of natural gas from shale formations. Clim Chang. 2011;106:679–690. http://dx.doi.org/10.1007/s10584-011-0061-5
14. Jiang M, Griffin WM, Hendrickson C, Jaramillo P, VanBriesen J, Venkatesh A. Life cycle of greenhouse gas emissions of Marcellus shale gas. Environ Res Lett. 2011;6(3):1–9. http://dx.doi.org/10.1088/1748-9326/6/3/034014
15. Cathles LM, Brown L, Taam, M, Hunter A. A commentary on 'The greenhouse-gas footprint of natural gas in shale formations' by R.W. Howarth, R. Santoro, and Anthony Ingraffea. Clim Chang. 2012;113:525–535. http://dx.doi.org/10.1007/s10584-011-0333-0
16. General Accountability Office (GAO). Federal oil and gas leases: Opportunities exist to capture vented and flared natural gas, which would increase royalty payments and reduce greenhouse gases. GAO-11–34. Washington DC: US GAO; 2010. Available from: http://www.gao.gov/new.items/d1134.pdf.
17. Forster D, Perks J. Climate impact of potential shale gas production in the EU. Report for European Commission DG CLIMA, report no AEA/R/ED57412. Didcot, Oxfordshire: AEA; 2012. Available from: http://ec.europa.eu/clima/policies/eccp/docs/120815_final_report_en.pdf
18. Broderick J, Anderson K, Wood R, Gilbert P, Sharima M, Footitt A, et al. Shale gas: An updated assessment of the environmental and climate change impacts. A report commissioned by the co-operative and undertaken by researchers at the Tyndall Centre, University of Manchester [document on the Internet]. c2011 [cited 2014 Feb 25]. Available from: http://www.tyndall.ac.uk/sites/default/files/coop_shale_gas_report_update_v3.10.pdf
19. Stephenson T, Valle JE, Riera-Palon X. Modelling the relative GHG emissions of conventional and shale gas production. Environ Sci Technol. 2011;45:10757–10764. http://dx.doi.org/10.1021/es2024115
20. Lechtenböhmer S, Dienst C, Fischedick M, Hanke T, Langrock T, Assonov SS, et al. Greenhouse gas emissions from the Russian natural gas export pipeline system. Wuppertal/Mainz: Wuppertal Institute and Max Planck Institute; 2005.
21. Eskom. Annual report 2012. Johannesburg: Eskom; 2012. Available at: http://www.eskom.co.za
22. Bradbury JA, Obeiter M, Draucker L, Wang W, Stevens A. Clearing the air: Reducing upstream greenhouse gas emissions from US natural gas systems. WRI working paper. Washington DC: World Resources Institute; 2013. Available from: http://pdf.wri.org/clearing_the_air_full_version.pdf.
23. Skone TJ, Littlefield J, Marriott J. Life cycle gas inventory of natural gas extraction delivery and electricity production. Final report 24 Oct 2011 (DOE/NETL-2011/1522). Pittsburgh, PA: US Department of Energy, National Energy Technology Laboratory; 2011.